

# Quark Matter Production in Heavy Ion Collisions<sup>1</sup>

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## 1 Introduction

The study of high energy heavy ion collisions is presently a very active field in experimental particle physics, with the RHIC collider in operation at BNL since summer 2000 and with the ALICE experiment being prepared to study this kind of physics at the LHC energies. The first goal of this experimental program, which started in 1986, with the AGS and SPS fixed-target programs, is the discovery of the phase transition from confined hadronic matter to deconfined partonic matter. The idea that such a phase transition should exist, between hadronic and quark matter, is around since the first models of the quark structure of hadrons. It is presently studied in detail in the framework of Lattice QCD calculations, which predict its occurrence when the temperature of the system exceeds a critical threshold at around 170 MeV, corresponding to a critical energy density of around 600 MeV/fm<sup>3</sup> [1]. Figure 1 illustrates how the energy density (in units of  $T^4$ ) depends on the temperature of the medium (in units of  $T_c$ ), increasing by an order of magnitude within a very small temperature range. At the critical temperature, two phenomena should occur: the color degrees of freedom become deconfined and chiral symmetry (spontaneously broken in the hadronic world) gets restored. Both should lead to observable effects, to be looked for in properly designed experiments. The proof of existence of the quark matter phase and the study of its properties are key issues in QCD, for the understanding of confinement and chiral-symmetry.

When this new state of matter was postulated, some signatures of its formation in high energy nuclear collisions were proposed, on the basis of theoretical arguments, among which we can highlight the enhancement of strange particle production, the suppression of charmonia states ( $J/\psi$ ,  $\chi_c$  and  $\psi'$ ), due to the screening of the  $c\bar{c}$  binding potential in the QGP colour soup, and the production of thermal dileptons, electromagnetic radiation emitted by the ‘free’ quarks. The results obtained by the SPS experiments, after 15 years of collecting data with proton and ion beams, provide “compelling evidence for the existence of a new state of matter, in which quarks roam freely”, produced in central Pb-Pb collisions at the highest SPS energies. Among the most exciting observations are the enhanced production of multistrange hyperons, the

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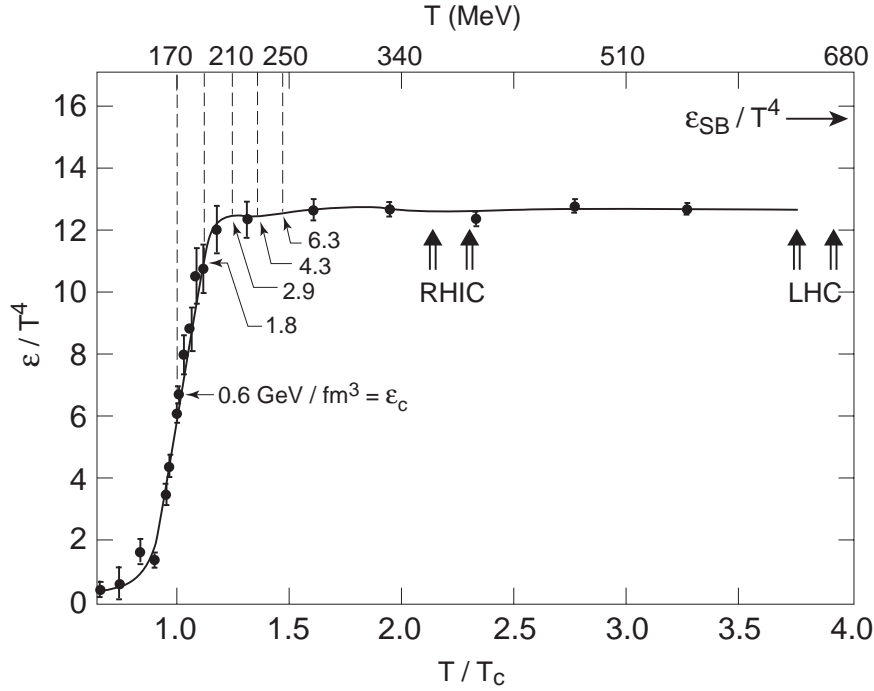


Figure 1: Energy density versus temperature, showing a phase transition at a critical temperature  $T_c \sim 170$  MeV.

centrality dependence of the  $J/\psi$  suppression pattern and the enhancement of intermediate mass dimuon production, a possible indication of thermal dimuons. Besides, the enhanced production of low mass dileptons may be an indication of approach to chiral symmetry restoration.

In view of these exciting results and in order to clarify important questions remaining open, a new experiment, NA60, has been approved at CERN, extending the SPS runs with heavy ion beams and bridging the gap between the original SPS program and the future high-energy wonderland of ALICE. At the other end of the energy scale, the NA49 experiment will have a ten day extension with Pb ions at 20 and 30 GeV per nucleon, to complete the energy scan of global strangeness production. So far it has collected data at 158, 40 and 80 GeV per nucleon. This extension of the SPS heavy ion running time will bring to a proper conclusion the program started in 1986, whilst providing valuable information, complementary to the studies underway at RHIC.

Here I review some of the most interesting results obtained by the CERN SPS experiments, with particular emphasis on the progress made in the last two years (since the Quark Matter 1999 conference). I will also present some pertinent questions that still remain open and explain how the future SPS program will address those issues.

The very large amount of experimental results obtained by the CERN SPS exper-

iments since 1986 is so vast and diversified that a proper review would require a much more extensive article, jointly prepared by several of the active players in the field. The Quark Matter 1999 conference, the last one before the RHIC experiments started collecting data, ended with two summary talks that reviewed in detail the status of the field in terms of hadronic [2] and dilepton [3] signals. A few attempts have also been made to see in a coherent way some of the most significant results, in particular those obtained with the lead beam at the SPS [4]. A tentative summary has been proposed [5], basically saying that “the combined results provide compelling evidence for the existence of a new state of matter, featuring many of the characteristics of the primordial soup in which quarks and gluons existed before they clumped together as the universe cooled down”.

We can discuss at length the scientific meaning (and opportunity) of these words, but it is certainly appropriate to say that all the CERN SPS experiments have been successful in delivering significant information, many of them having seen “what they were looking for”.

However, these 15 years have also confirmed that heavy ion collisions lead to very complicated (and fastly evolving) systems, and that it is difficult to extract clear messages from the observations. Central collisions between two Pb nuclei, at the highest SPS energies, lead to the production of hundreds of final-state particles widely emitted without discernible structures. These complex, and apparently chaotic, final states can be studied applying statistical concepts, attempting descriptions based on (non-perturbative) QCD thermodynamics, and summarized by macroscopic variables like temperature, pressure, etc. But such studies present formidable challenges, requiring complex (and quite expensive) experimental techniques, demanding huge amounts of computing time, and leading, after a major effort of many people, to a few points on a figure, not always easy to interpret. In spite of the strong indications that very interesting phenomena occur in the early stages of a Pb-Pb collision, at the highest SPS energies, we still do not know the final answer to the critical question that motivates this field: can we convince ourselves and the community at large that we have formed quark matter in the laboratory?

The final clarification of the present SPS results requires a careful and systematic approach, to establish beyond reasonable doubt that the QCD phase transition from hadronic to quark matter happens in central Pb-Pb collisions at the highest SPS energies. Further work on the available data remains to be done and, in some cases, where information is obviously missing, new measurements should be urgently performed. Models that claim to explain the available results must provide specific predictions for future measurements, with appropriate and carefully explained uncertainty bands. When and if the new observations validate those predictions, we will have made substantial progress in our understanding.

## 2 Overview of heavy ion collisions at the SPS

To recognise specific features of heavy ion collisions with respect to a simple superposition of nucleon-nucleon interactions, it is very important to make a ‘scan’ in the centrality of the events. While the most peripheral collisions should be similar to conventional physics, the most central and violent events, where the two nuclei collide head-on, are expected to reveal some kind of ‘anomalous’ behaviour.

The centrality variables, like the impact parameter,  $b$ , or the number of participant nucleons,  $N_{\text{part}}$ , can be determined from directly measured quantities, such as the charged hadron multiplicity,  $N_{\text{ch}}$ , the transverse energy,  $E_{\text{T}}$ , and the zero degree (forward) energy,  $E_{\text{ZDC}}$ . Assuming that  $N_{\text{ch}}$  and  $E_{\text{T}}$  are directly proportional to  $N_{\text{part}}$  or, similarly, that  $E_{\text{ZDC}}$  scales linearly with the number of spectator nucleons from the projectile ion (wounded-nucleon model [6]) it is possible to describe with good accuracy the measured distributions in the framework of the Glauber model of nucleus-nucleus collisions. A typical example [7], using  $N_{\text{ch}}$ , can be seen in Fig. 2.

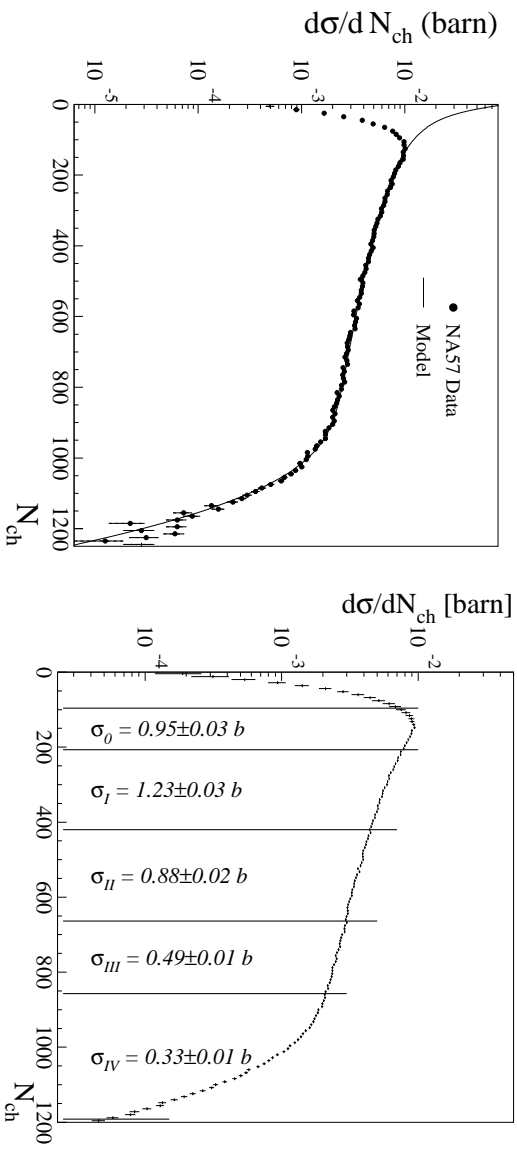


Figure 2: The charged hadron multiplicity distribution measured by NA57 adjusted by the wounded-nucleon model (left) and illustrating the splitting of the event sample in different centrality classes (right).

Figure 3 illustrates an alternative way to measure the centrality of the collisions, using the forward energy measured in a hadronic calorimeter placed in the beam line (at zero degree). If the incident Pb beam ion traverses the target without interacting, all the energy ( $208 \times 158$  GeV, or 33 TeV) is deposited in the calorimeter, resulting in the ‘beam peak’ seen in the figure. This figure also illustrates the fact that the experiments can select the collected events, at the trigger level, according to the centrality of the collisions. This is particularly useful to increase the relative fraction of central events in the collected data. Without this feature, many experiments would almost only collect the much more frequent peripheral collisions, lacking statistics in the most interesting region.

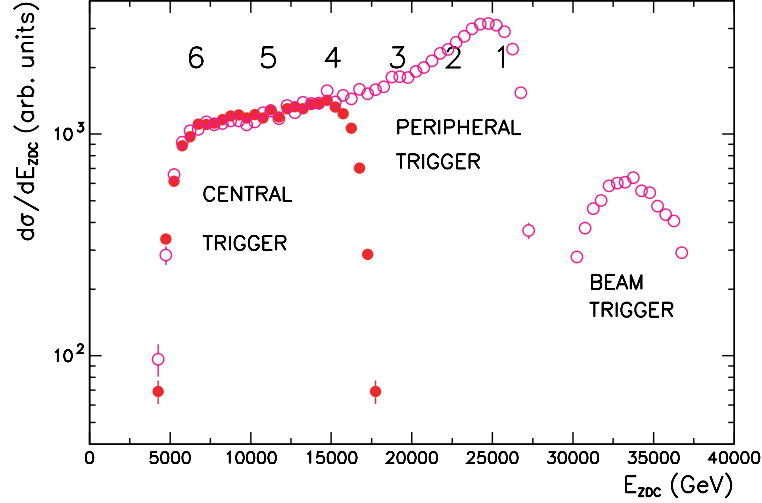


Figure 3: Forward energy distributions measured by the NA50 zero degree calorimeter, for three different event samples selected at the trigger level.

Figure 4 shows the baryon rapidity distributions, in the center of mass system, for central Pb-Pb collisions, compared to the S-S and pp distributions, scaled up to match the number of nucleons participating in the Pb-Pb collisions. The broad peaks at rapidities around 1.5 correspond to the projectile and target nucleons, shifted to mid rapidities from the beam and target rapidities due to the loss of energy induced by their mutual traversing (an effect commonly known as ‘stopping’). The S beam had an energy of 200 GeV per incident nucleon, while the Pb beam was less energetic, 158 GeV per nucleon, therefore having a somewhat smaller ‘beam rapidity’. However, the reason why the Pb peaks are closer to mid rapidity than the S peaks is mostly due to the fact that the Pb nuclei are much bigger, thereby being much more effective in ‘stopping’ each other.

Most of the particles newly produced in a heavy ion collision, like pions and kaons, for instance, are produced at mid-rapidity, after the two colliding nuclei crossed each other. Figure 5 shows the pseudo-rapidity distributions of charged particles produced in Pb-Pb collisions, at 158 GeV per nucleon (left) and at 40 GeV per nucleon (right), for several different centrality classes, tagged by the  $E_{ZDC}$  energy of the events.

Besides the number (or rapidity density) of produced charged particles and the total forward energy measured in a zero degree calorimeter, also the flux of energy released in the transverse plane,  $E_T$ , provides a good estimator of the geometry of the heavy ion collision. In fact, the measurement of  $E_T$  is essentially equivalent (but much easier to do experimentally) to the measurement of the total multiplicity of produced particles (mostly pions), from the point of view of sampling the events in different centrality classes. It is actually a remarkable observation that the ratio between  $E_T$  and number of produced charged particles remains essentially constant from the most peripheral to the most central collisions (this remains valid at the higher energies of RHIC [8]).

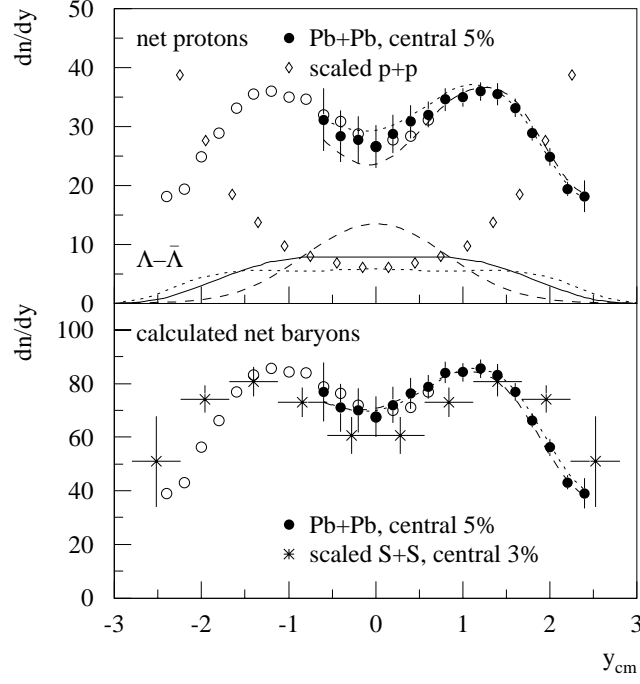


Figure 4: Rapidity distributions of baryons for central Pb-Pb collisions, compared to scaled S-S and pp distributions.

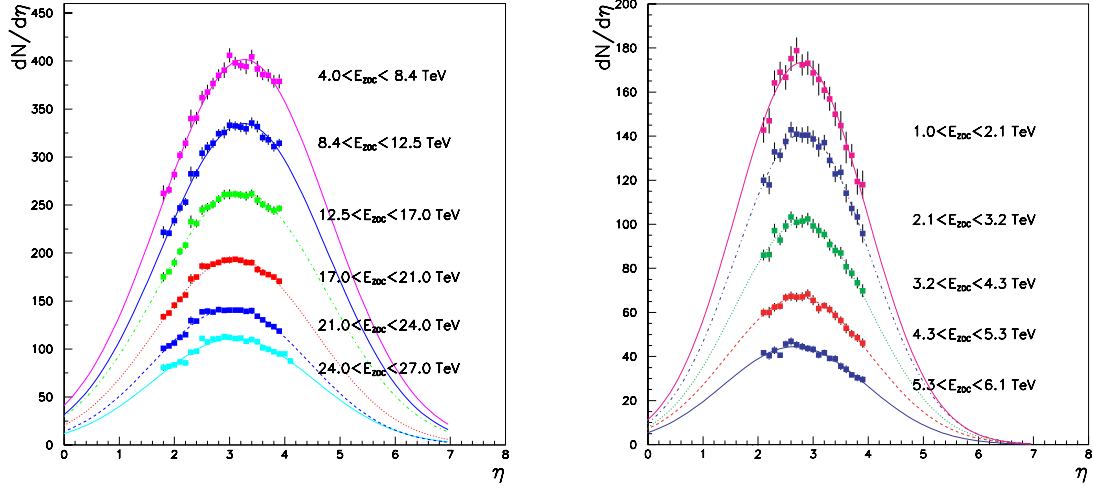


Figure 5: Pseudo-rapidity distributions of charged particles produced in Pb-Pb collisions of different energies and centralities, as measured by the NA50 experiment. The data points are fitted with gaussians.

Figure 6 shows the transverse energy distributions of S-Au and Pb-Pb collisions, as measured by the NA35 and NA49 experiments, with calorimeters placed at mid-rapidity. Besides allowing to tag the events from peripheral to central collisions, the measurement of the transverse energy rapidity density, at mid-rapidity, is very important for the estimation of the energy density,  $\epsilon$ , reached in these collisions. Figure 7 shows that the value 400 GeV is reached in central Pb-Pb collisions at the highest SPS energies [9].

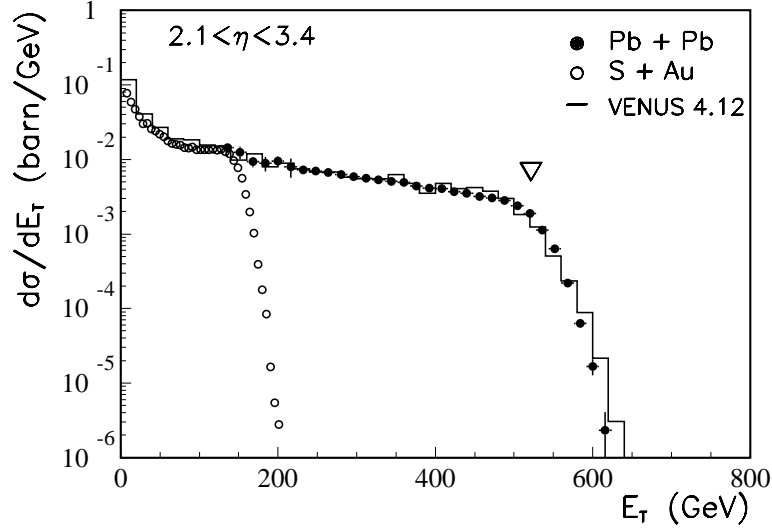


Figure 6: Transverse energy distributions of S-Au and Pb-Pb collisions, from NA35 and NA50. The Pb data are compared to a calculation done with the VENUS monte carlo event generator.

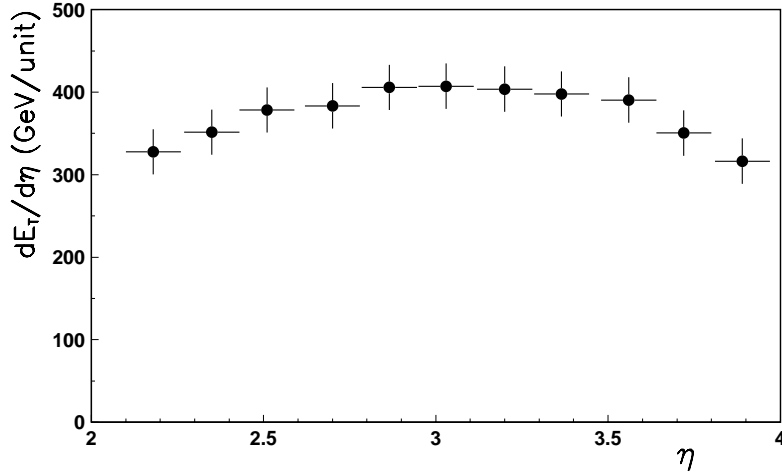


Figure 7: Rapidity density of the transverse energy emitted in Pb-Pb collisions, as measured by NA49. At mid-rapidity, 2.92, the value 400 GeV per unit rapidity is observed.

From the measured values of mid-rapidity  $dE_T/dy$ , the energy density can be estimated according to the formulation proposed by Bjorken almost 20 years ago [10], assuming a boost-invariant longitudinal expansion. The estimates give  $\epsilon \sim 3.2 \text{ GeV/fm}^3$  for central Pb-Pb interactions [9], significantly higher than the value 600-700 MeV/fm<sup>3</sup> calculated in Lattice QCD for the occurrence of the phase transition [1]. The Table 1 shows the corresponding estimates for smaller collision systems, S-S and S-Au.

Table 1: Values of the energy density,  $\epsilon$ , reached in some collision systems studied at the SPS, estimated according to the Bjorken model.

System	$E_{\text{lab}}/A$ (GeV)	$N_{\text{part}}$	$\epsilon$ (GeV/fm <sup>3</sup> )
S - S	200	58	1.3
S - Au	200	113	2.6
Pb - Pb	158	390	3.2

### 3 Strangeness production

One of the earliest predictions in the field of high energy heavy ion physics is that particles containing strange quarks should be produced more often if the produced system goes through a quark-gluon plasma phase. An increase of around a factor 2 has indeed been observed [11], in global strangeness production, when comparing heavy ion to elementary collisions, at around the same colliding energies, as can be seen in Fig. 8.

Global strangeness yields are dominated by kaon production (around 75 % of all the produced strange particles). Figure 9 shows how the kaon multiplicity, per produced pion, evolves with the system size, from peripheral to central Pb-Pb collisions, including points from some other (smaller) colliding systems. These measurements were done, in particular, by the NA49 large-acceptance experiment [12].

The most spectacular observations have been done, however, in the multi-strange hyperon sector. The very large enhancement factors in particle yields per participating nucleon (see Fig. 10), reaching a factor around 17 for the  $\Omega$ , a triple strange hyperon, and the fact that these factors are significantly higher for the states with more strange quarks, i.e.  $E_\Omega > E_\Xi > E_\Lambda$ , where  $E_i$  is the enhancement of the particle  $i$  with respect to p-A interactions, are naturally explained if the particle yields are determined from statistical hadronization of a strangeness-enhanced plasma phase. On the contrary, such enhancement levels cannot be reproduced in conventional (final state hadronic rescattering) scenarios, given the short lifetime of the expanding hadronic system (see, however, the recent work mentioned in Ref. [13]). When these results were presented in the Quark Matter 1999 conference [14], a question was left in



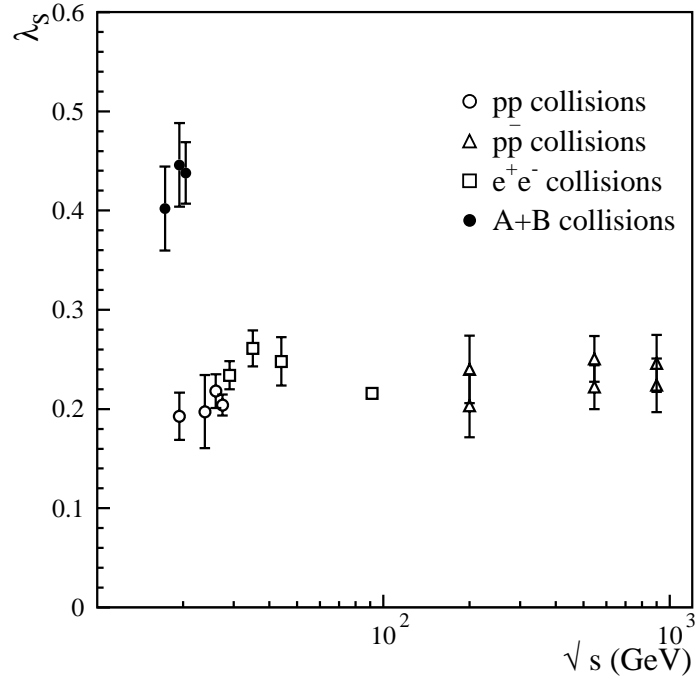


Figure 8: The strangeness suppression factor,  $\lambda_s$ , for the production of strange quarks with respect to the production of  $u$  and  $d$  quarks, as a function of the collision energy, for elementary and nuclear collisions.

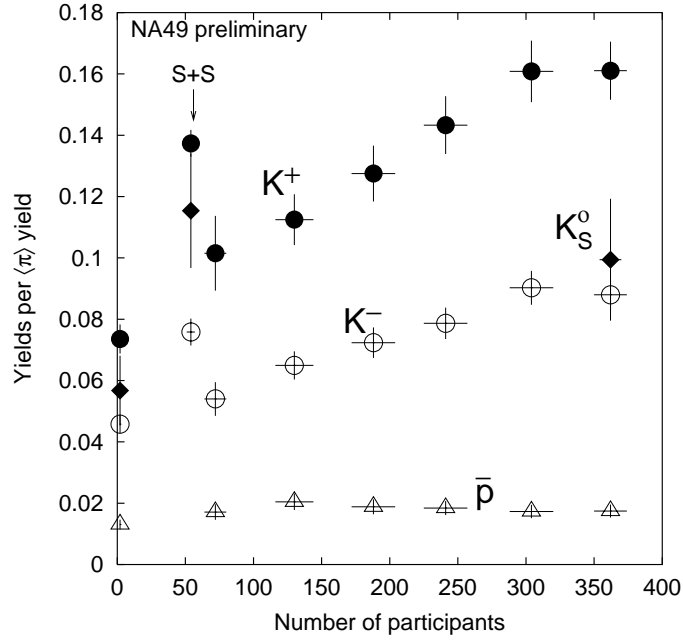


Figure 9: Production yield of kaons (and anti-protons), normalized to pion production, versus the number of nucleons involved in the pp, S-S and Pb-Pb collisions.

the air: is there a threshold behaviour in the enhancement pattern, between the p-Be and p-Pb points and the Pb-Pb values? The flat pattern observed in the Pb-Pb data indicated very little dependence on the centrality of these collisions, for  $N_{\text{part}} > 100$ . Where was the transition?

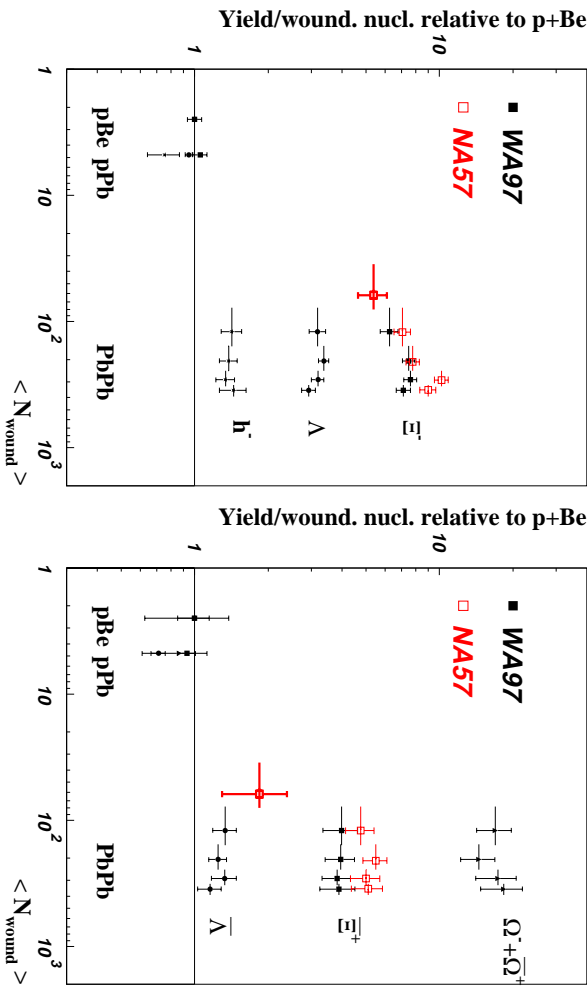


Figure 10: Multi-strange hyperon production yields, at mid-rapidity, per wounded nucleon, normalized to the p-Be system, as a function of the number of wounded nucleons. The right panel collects the particles with no valence quark in common with the colliding nucleons.

The NA57 experiment has continued these studies, making a special effort to collect peripheral Pb-Pb collisions. The first results were presented at the Quark Matter 2001 conference [15]. They show, as can be seen in Fig. 10, that the enhancement of  $\Xi^+$  production increases by a factor 2.6, from  $N_{\text{part}} = 62$  to 121. The confirmation of a threshold behaviour in the strangeness enhancement pattern may come from the data analysis of the other strange hyperons. Unfortunately, having only five bins in centrality, and four of them showing a flat behaviour, the Pb-Pb pattern measured by the NA57 experiment will fall short of showing a clear transition, with a characteristic threshold, if it exists. A better understanding of the apparent onset of the enhancement would require studying ‘intermediate mass’ nuclear collisions, like In-In, for instance, in small centrality steps. Unfortunately, the effort required by the preparation of the ALICE experiment seems to prevent the realisation of such future studies.

Another major addition to the strangeness chapter is being provided by the NA49 experiment, when running with proton beams. The very large acceptance of this experiment makes it particularly appropriate in the study of asymmetric collision systems, as p-A interactions, where the reflection of the probed phase space window around midrapidity cannot be performed. First results of “NA49-hadrons” have also

been shown at the Quark Matter 2001 conference [16], raising some questions on the “p-A reference baseline” used by WA97/NA57 in the extraction of the enhancement factors. Fortunately, we will see further data on this issue in the near future, since “NA49-hadrons” has been approved for further running in the next few years, and NA57 will collect more data on proton induced collisions in 2001.

Still in the strangeness sector, long standing questions concerning  $\phi$  production remain unclear. NA50 sees, in the dimuon decay channel, a strong increase in the yield of  $\phi$  mesons produced in heavy ion collisions and a transverse mass spectrum with a rather low ‘inverse slope’ [17], contrary to the observations of the NA49 experiment [18], in the  $K^+K^-$  decay channel. Future measurements of low- $p_T$   $\phi$  production in the dilepton channel, by NA60, should help clarifying the source of discrepancy.

## 4 Evolution of the final state

The understanding of the particle multiplicities (or relative production yields) and of their kinematical distributions, gives significant information on the properties of the system that, by hadronization, resulted in the observed final states. The hadronic data collected at the SPS, in particular with high energy Pb-Pb collisions, has been studied in the framework of statistical models of the hadronization process. The data collected in the large acceptance NA49 detector have been particularly useful for these studies, and to fix the free parameters of the models, such as the chemical freeze-out temperature, the baryon chemical potential, etc.

Figure 11 shows several measurements of ratios of particles yields (points), compared to values calculated (lines) in a particular statistical model [19], where the hadrons are produced as a gas in complete chemical equilibrium, with a chemical freeze-out temperature of 168 MeV and a baryon chemical potential of 266 MeV. Given the fact that this temperature is very close to the value expected for the phase transition to the QGP phase, it is tempting to imagine that the system crosses the phase boundary, from the partonic to the hadronic phases, shortly before the chemical freeze-out point. Furthermore, the almost complete strangeness saturation assumed in these models indicates that the observed strangeness enhancement comes essentially from the partonic phase.

Once the hadrons are produced, the chemistry step is over but the particles continue to collide with each other, influencing their kinetics. It is only later, once the system has expanded further, that the particles stop interacting and fly through to the detectors. This ‘thermal freeze-out’ point can be probed by looking at the transverse mass spectra of identified particles, for instance. The flux of particles in the transverse plane is purely due to the production mechanisms taking place during the collision, while in the longitudinal direction things are made more complicated by the very high initial-state energy of the colliding nuclei. The NA44, NA49 and WA97 experiments, among others, have shown that all the hadrons exhibit exponential transverse mass spectra, that can be simply characterized by the temperature of

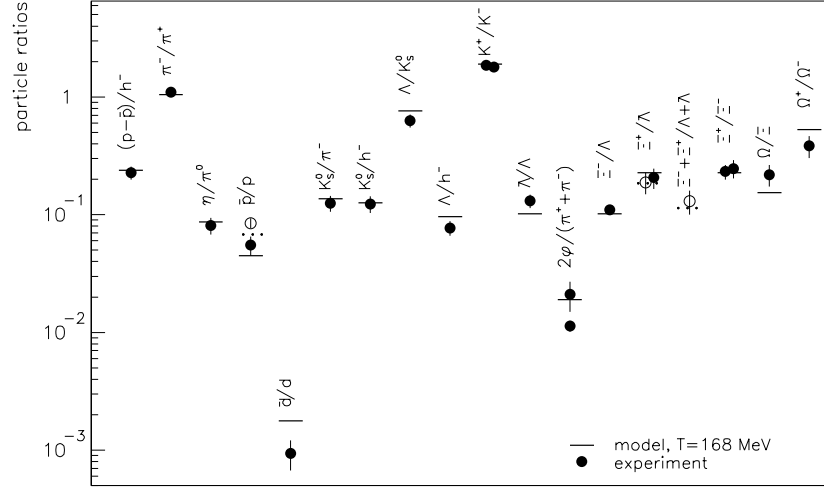


Figure 11: Comparison of particle yields measured in Pb-Pb collisions, at the SPS, with the values expected in a thermodynamical model assuming statistical particle production from a thermal bath.

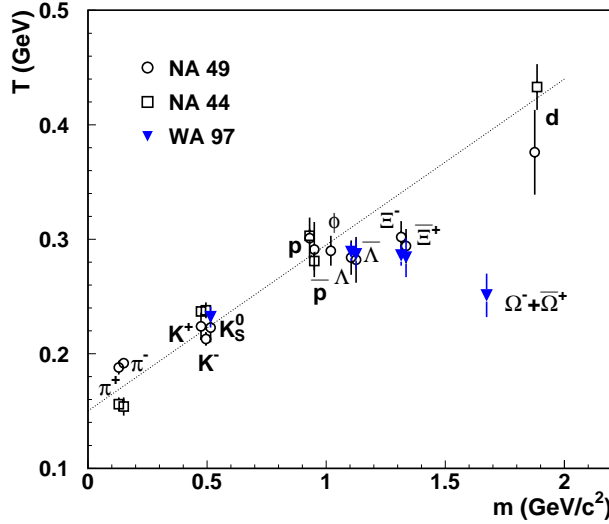


Figure 12: Inverse slope,  $T$ , of the exponential  $m_T$  spectra, as a function of the mass of the produced particle, for Pb-Pb collisions at the highest SPS energies.

the medium at thermal freeze-out,  $T_f$ , and by the mean transverse flow velocity of the medium,  $\langle v_\perp \rangle$ . These two values determine the inverse slope of the transverse mass distributions, for each particle species, roughly as  $T_f + 0.5 \cdot m_0 \cdot \langle v_\perp \rangle^2$ . This linear dependence with the mass of the produced particles,  $m_0$ , can be seen in Fig. 12 [20].

These observations show that the thermal motion of each produced hadron is superimposed on the ordered collective flow of the whole system, due to the radially expanding fireball, looking like a microscopic version of the Big Bang [21]. The

departure of the  $\Omega$  from the linear trend may be due to an early decoupling (freeze-out) of this particle, probably because, having zero isospin, it cannot form resonances with the copious pions, that substantially contribute to the equilibration of the other hadrons [22].

To separately determine the radial flow velocity and the freeze-out temperature of the system, it is very important to have other, independent, sources of information. For instance, the transverse flow of the system can also be seen through its influence on the Bose-Einstein pion correlations [23]. By following the dependence of the HBT transverse radius on the transverse momentum of the pion pair (see Fig. 13), it is possible to extract the correlation between the radial flow velocity and the freeze-out

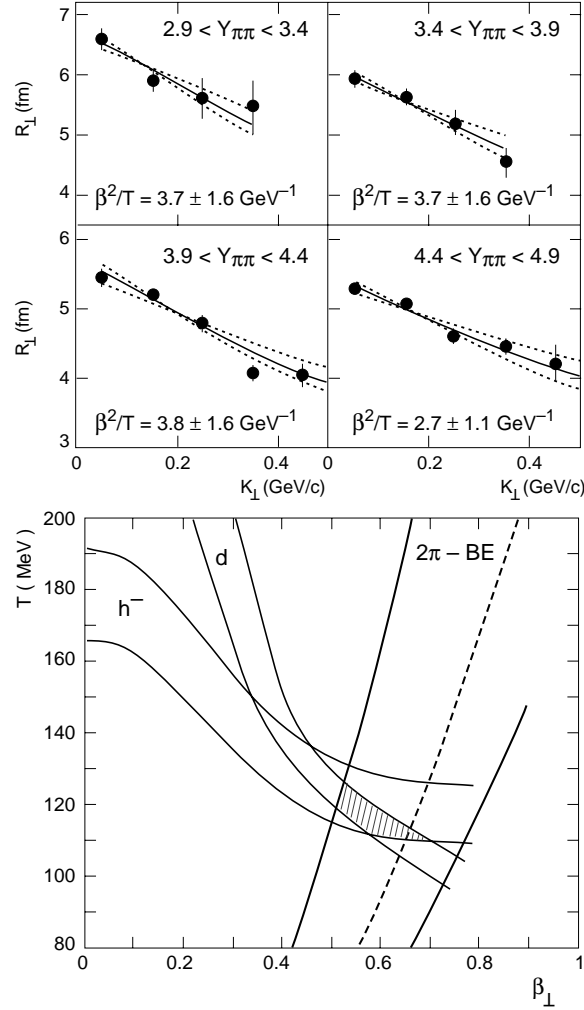


Figure 13: Dependence of the transverse radius of the produced system on the transverse momentum of the pion pair, for several rapidity ranges (top) and correlation between thermal freeze-out temperature and radial flow velocity for central Pb-Pb collisions (bottom).

temperature of the system. Fortunately, the combination of this correlation with the information obtained from the study of the hadronic transverse mass spectra, allows to separate the random thermal motion from the collective flow, as can be seen in Fig. 13, leading to the values  $T_f \sim 100$  MeV and  $\langle v_\perp \rangle \sim 0.55 c$  [24].

## 5 Low mass dilepton production

The CERES experiment has observed [25] that the yield of low mass  $e^+e^-$  pairs measured in p-Be and p-Au collisions is properly described by the expected “cocktail” of hadronic decays, while in Pb-Au collisions, on the contrary, the measured yield, in the mass region 0.2–0.7 GeV, exceeds by a factor 2.5 the expected signal [26], as shown in Fig. 14.

Dileptons from  $\pi^+\pi^-$  annihilation would increase the expected yield around the mass of the  $\rho$  meson, not reproducing the measured shape. The excess dileptons are concentrated at low  $p_T$  (Fig. 15) and their yield seems to scale with the square of the charged particle multiplicity (Fig. 16).

These observations are consistent with the expectation that the properties of vector mesons should change when produced in dense matter. In particular, near the phase transition to the quark-gluon phase, chiral symmetry should be partially restored, making the vector mesons indistinguishable from their chiral partners, thereby inducing changes in their masses and decay widths [27]. The short lifetime of the  $\rho$  meson, shorter than the expected lifetime of the dense system produced in the SPS heavy ion collisions, makes it a sensitive probe of medium effects and, in particular, of chiral symmetry restoration.

The present measurements are not accurate enough to clearly distinguish between a change in the  $\rho$  mass (signaling the restoration of chiral symmetry) and a broadening due to conventional hadronic interactions [28]. Already E. Shuryak [29] and B. Müller [30], in their Quark Matter 1999 papers, emphasized the importance of a considerable improvement in the CERES measurements of low mass dilepton production, in terms of signal to background ratio, mass resolution, and statistics. A TPC was added to the CERES setup [31], to improve the momentum resolution of the dielectron measurement. Unfortunately, problems in the data taking during year 1999 have prevented the CERES experiment from collecting a significant sample of dilepton events [32]. Those problems were solved in time for the run of year 2000 and we are eagerly waiting for the results from this new data set. A first look into this new data sample indicates that a mass resolution close to the expected value of around 2% may be within reach. Unfortunately, the collected statistics will probably not be enough to have an accurate measurement of the  $\omega$  resonance, which would be very helpful in the studies of the in-medium modifications apparently affecting the  $\rho$ .

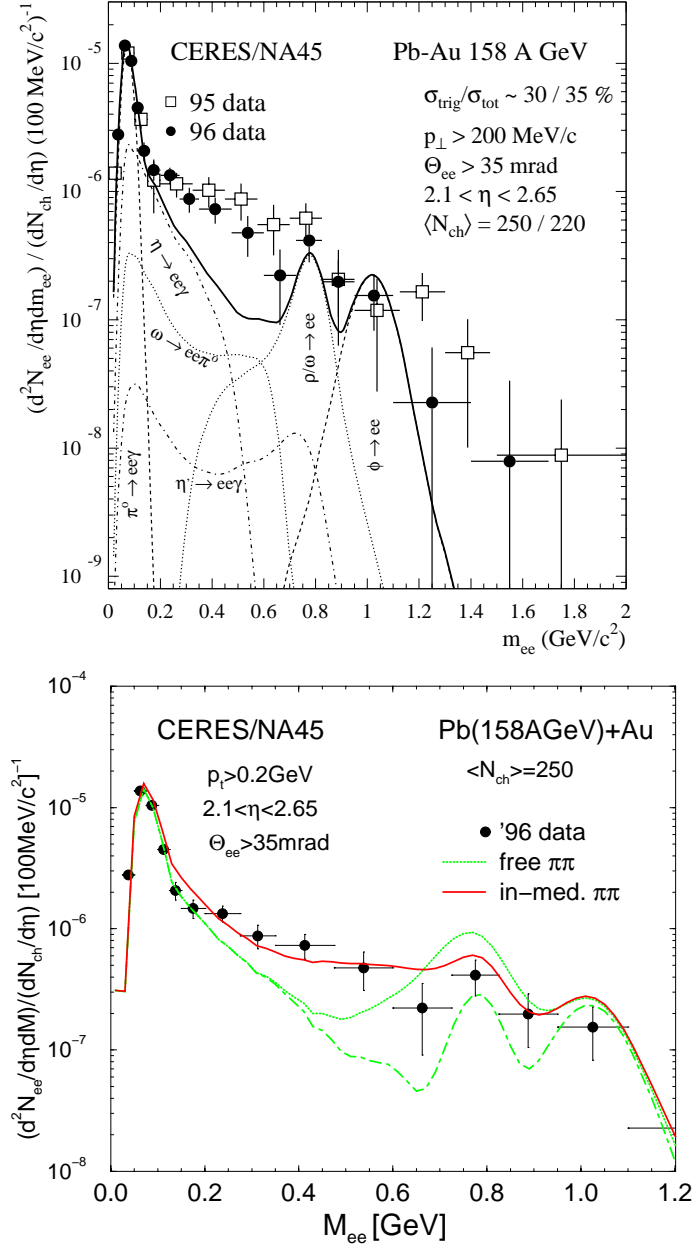


Figure 14: Dielectron mass distribution measured by CERES in Pb-Au collisions, compared to the expected hadronic decays (top) and to the contribution from  $\pi\pi$  annihilation with and without in medium effects (bottom).

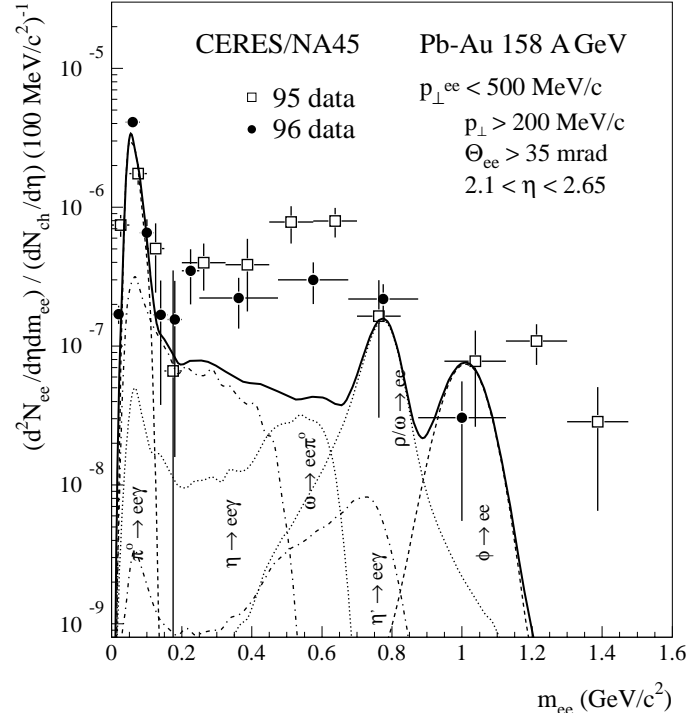


Figure 15: Mass distribution of low  $p_T$  dielectrons produced in Pb-Au collisions, as measured by CERES.

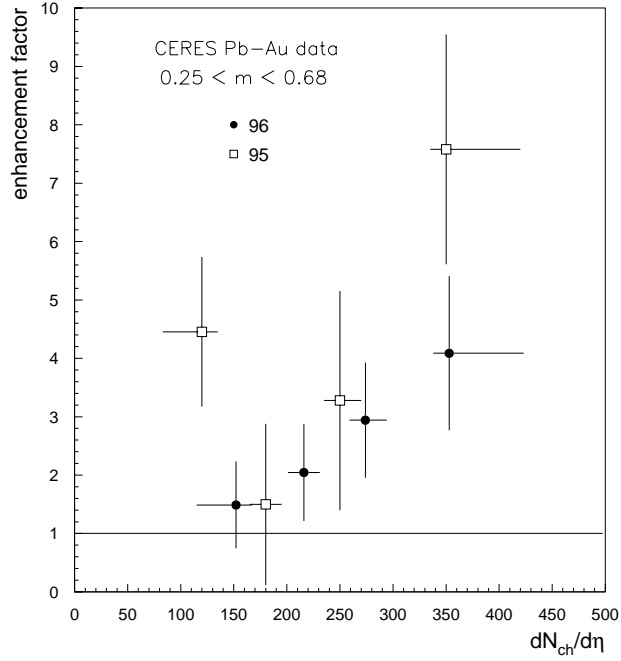


Figure 16: Yield of excess dileptons versus the charged particle multiplicity. Is there an onset at  $dN_{ch}/d\eta \sim 100$  ?



## 6 Intermediate mass dilepton production

The NA38 and NA50 experiments have studied [33] the production of dileptons in the mass window between the  $\phi$  and the  $J/\psi$  peaks, as a superposition of Drell-Yan dimuons and simultaneous semileptonic decays of  $D$  and  $\bar{D}$  mesons, after subtraction of the combinatorial background from pion and kaon decays [34].

The Drell-Yan and open charm contributions were calculated with the PYTHIA event generator [35] with the MRS A set of parton distribution functions [36]. PYTHIA describes reasonably well [37] the kinematics and cross sections (including the energy dependence) of  $D$  meson hadroproduction, as well as the semi-leptonic decays and corresponding lepton distributions. Figure 17 shows that the dimuon mass spectra measured in p-A collisions are very well reproduced taking the high mass region to normalize the Drell-Yan component and an open charm cross-section in good agreement with direct measurements made by other experiments. The calculations do not

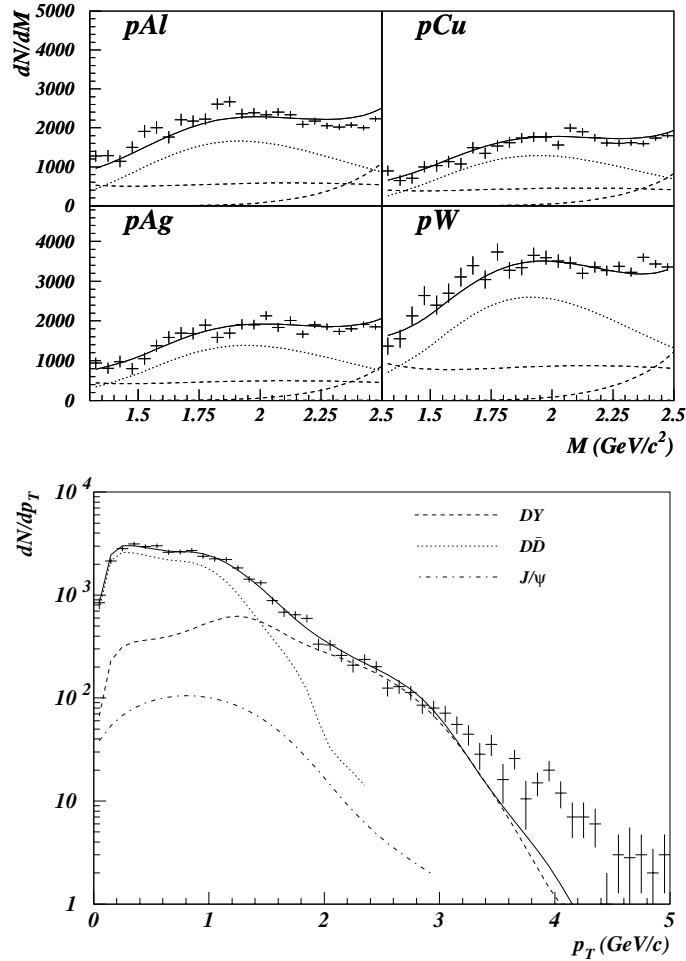


Figure 17: Dimuon mass (top) and  $p_T$  (bottom) distributions measured in p-A collisions by NA50, compared to the corresponding expected sources.

include NLO QCD diagrams, particularly important for high  $p_T$  Drell-Yan production. On the contrary, the superposition of Drell-Yan and open charm contributions, with the nucleon-nucleon absolute cross sections scaled with the product of the mass numbers of the projectile and target nuclei (as expected for hard processes), fails to properly describe the dimuon yield measured in ion collisions.

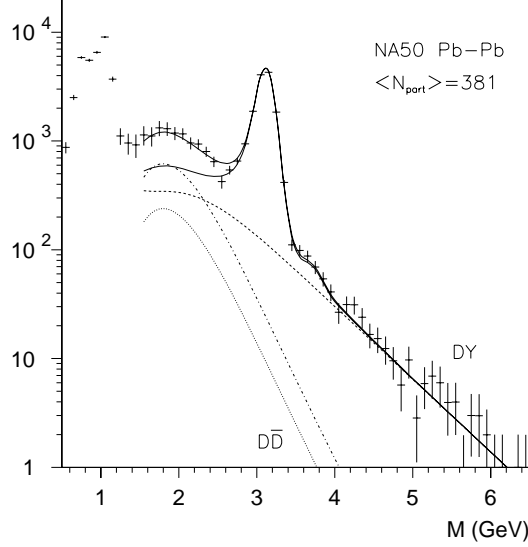


Figure 18: Dimuon mass distribution measured in central Pb-Pb collisions, compared to the expected sources, with and without scaling up the charm contribution.

Figure 18 shows, for central Pb-Pb collisions, how the sum of the expected sources underestimates the measured data. The same figure shows that the data can be reproduced by simply increasing the open charm yield. The scaling factor by which the charm contribution should be multiplied to properly describe the measured spectra seems to grow linearly with the number of nucleons participating in the collision, as shown in Fig. 19. In this figure, the points “4-D analysis” are obtained with an improved deconvolution method to extract the physical kinematics from the measured values, affected by acceptance and finite resolution (smearing) effects. This analysis method accounts for physical correlations among kinematical variables and does not require any assumption on the specific shapes of their distributions [38].

The observed excess can be due to an overall enhancement of open charm production in heavy ion collisions [39]. An alternative explanation could be that the rescattering of the charm quarks or  $D$  mesons in the produced medium leads to a broader  $p_T$  distribution and would locally enhance the charm component in the limited phase space domain covered by NA50 [40]. However, recent studies [41] have shown that the data cannot be accounted for by this last model.

The observed excess can also be due to the production of thermal dimuons, a signal that was the original motivation for the NA38 experiment and that has been recently revisited [42, 43]. In particular, the intermediate mass dimuons produced

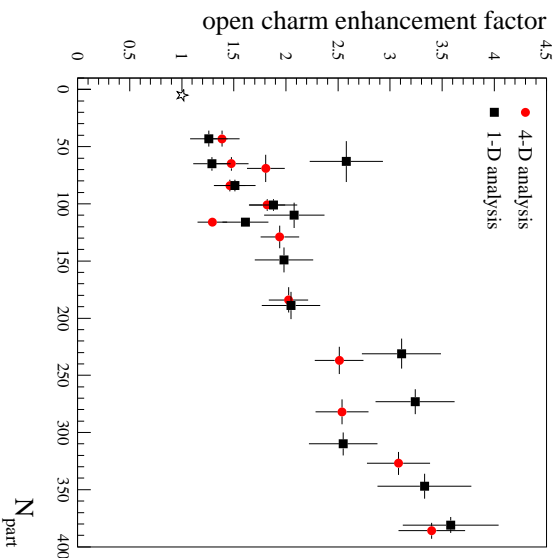


Figure 19: Dependence on the number of participants of the scaling factor by which the charm contribution must be multiplied to properly describe the measured spectra.

in the most central Pb-Pb collisions are well reproduced [41] by adding thermal radiation, calculated according to the model of Ref. [42], to the Drell-Yan and charm contributions normally extrapolated from nucleon-nucleon collisions. This model explicitly includes a QGP phase transition with a critical temperature of 175 MeV. The best description of the data is obtained using  $\sim 250$  MeV as the initial temperature of the QGP medium radiating the virtual photons. The presently available data cannot distinguish between an absolute enhancement of charm production and the emission of thermal dilepton radiation. The clarification of the nature of the physics process behind the observed excess is also in the wish lists presented by E. Shuryak and B. Müller in their Quark Matter 1999 papers, and is the strongest physics motivation of the NA60 experiment.

## 7 Charmonia production and suppression

The formation of a deconfined medium should induce a considerable suppression of the charmonia production rate, due to the colour ‘Debye’ screening of the  $c\bar{c}$  potential or to the breaking of the  $c\bar{c}$  binding by scattering with energetic (deconfined) gluons [44]. However, even the relatively simple measurement of  $J/\psi$  production faces a big challenge when it comes to furnish a convincing logical case that proves, to the satisfaction of the experts in the field, that a deconfined state of matter has been formed. It is not enough to show that a certain observable changes from p-Pb to Pb-Pb collisions, for instance, or to argue that its value in the most central nucleus-nucleus collisions is different from what is calculated in a ‘conventional physics’ model. The best path to clearly establish a solid result and shed light in this complicated field is

to build a robust set of measurements, that establishes a precise reference baseline, relative to which the specific behaviour of heavy ion collisions can be extracted. Such a baseline shows what is the ‘normal’ behaviour of the signal we are studying, with respect to which we look for changes due to QGP formation. Furthermore, we are in a much better position if nature provides us with a reference process, insensitive to the formation of a deconfined phase, specially if we can measure it with the same detector.

In the case of the  $J/\psi$  suppression topic, the baseline is built from the measurements done by NA38 and NA50 with pp, p-A and light ion collisions [45]. Very peripheral Pb-Pb collisions have been successfully collected in year 2000 and we will soon know how well they follow the “normal nuclear absorption” baseline. The best reference physics process, at SPS energies, is the rate of high mass Drell-Yan dimuons, since the Drell-Yan process can be precisely calculated and depends on the collision system in a well known way. Figure 20 shows absolute cross sections of Drell-Yan production measured by the NA38, NA51 and NA50 experiments in pp, p-D, p-W, S-U and Pb-Pb collisions, at several energies, divided by the corresponding values calculated at leading order with the MRS A parton distribution functions.

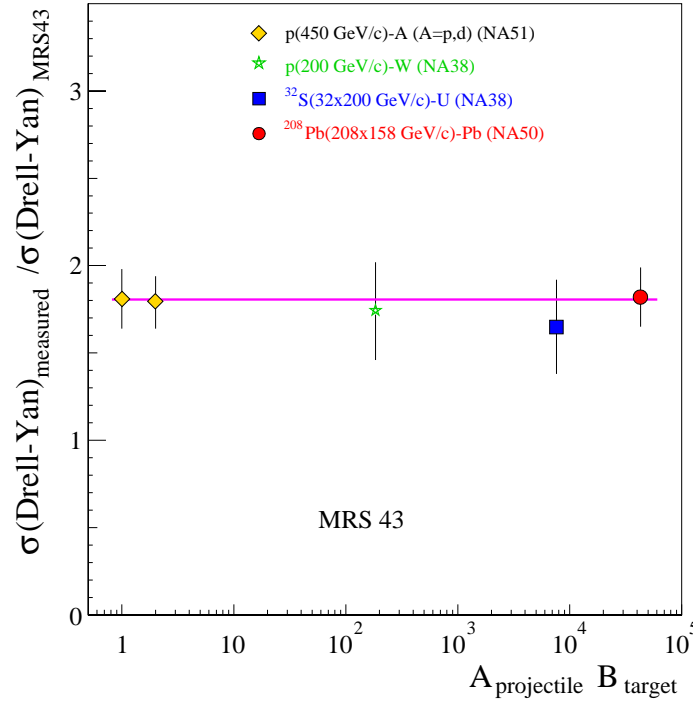


Figure 20: The measured yield of Drell-Yan dimuons follows the expected values, from pp to Pb-Pb collisions.

From the measured  $J/\psi$  production yields we can derive the  $J/\psi$  cross section per nucleon,  $B_{\mu\mu}^{\psi} \sigma^{\psi} / AB$ , displayed in Fig. 21 as a function of the product of the mass numbers of the two colliding nuclei. Contrary to what happens with the evolution

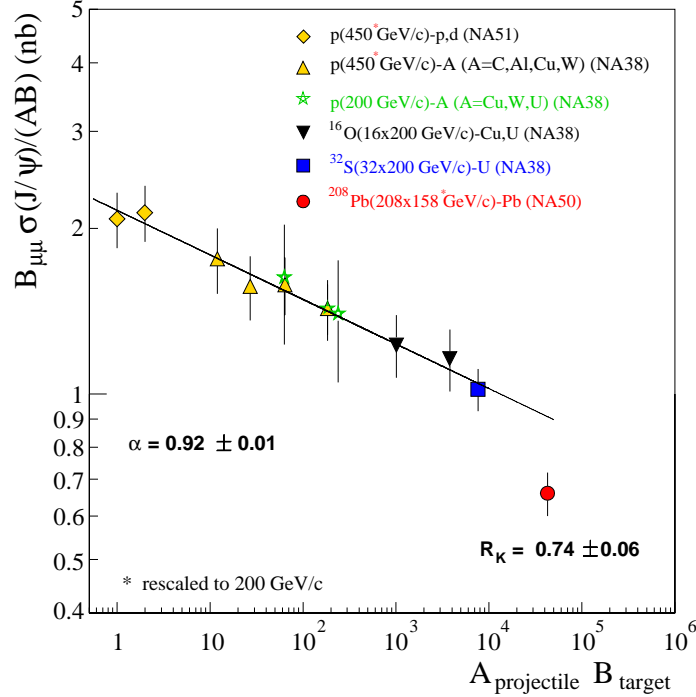


Figure 21: The  $J/\psi$  production cross section measured from pp to Pb-Pb collisions, in the NA38, NA51 and NA50 experiments.

of the Drell-Yan process, the Pb-Pb  $J/\psi$  point is completely different from the value indicated by the pattern established by the p-A and light ion measurements.

The peculiar behaviour of the Pb-Pb data can be seen in much more detail by binning the collected event sample as a function of the centrality of the collisions. Figure 22 shows how the  $J/\psi$  production rate, with respect to the yield of Drell-Yan dimuons, decreases from peripheral to central Pb-Pb collisions, using either  $E_{ZDC}$  or  $E_T$  to estimate the centrality of the reactions. The same figures show the “normal  $J/\psi$  absorption line”, determined by the reference data (from pp to S-U) shown in Fig. 21. The data points collected in the most central collisions show a very significant departure from the expected behaviour, while the most peripheral points seem to be in (rough) agreement with the absorption expected in normal nuclear matter.

The upper panel of Fig. 23 shows that the observed two-step suppression pattern is in clear disagreement with the predictions of the ‘conventional’ models [46, 47, 48, 49], that attribute the disappearance of the  $J/\psi$  mesons to interactions with ‘comoving’ hadrons. A first departure from the conventional curves is seen for collisions that release around 40 GeV of neutral transverse energy in the electromagnetic calorimeter of NA50. A second substantial drop is seen for the most central Pb-Pb collisions, while the hadronic models systematically predict a smooth absorption trend. On the other hand, a two-step pattern, as seen in the data, is naturally expected if the charmonia states are dissolved in a deconfined medium, due to the different melting temperatures of the  $\chi_c$  and  $J/\psi$  states (about 30–40 % of the observed  $J/\psi$  mesons

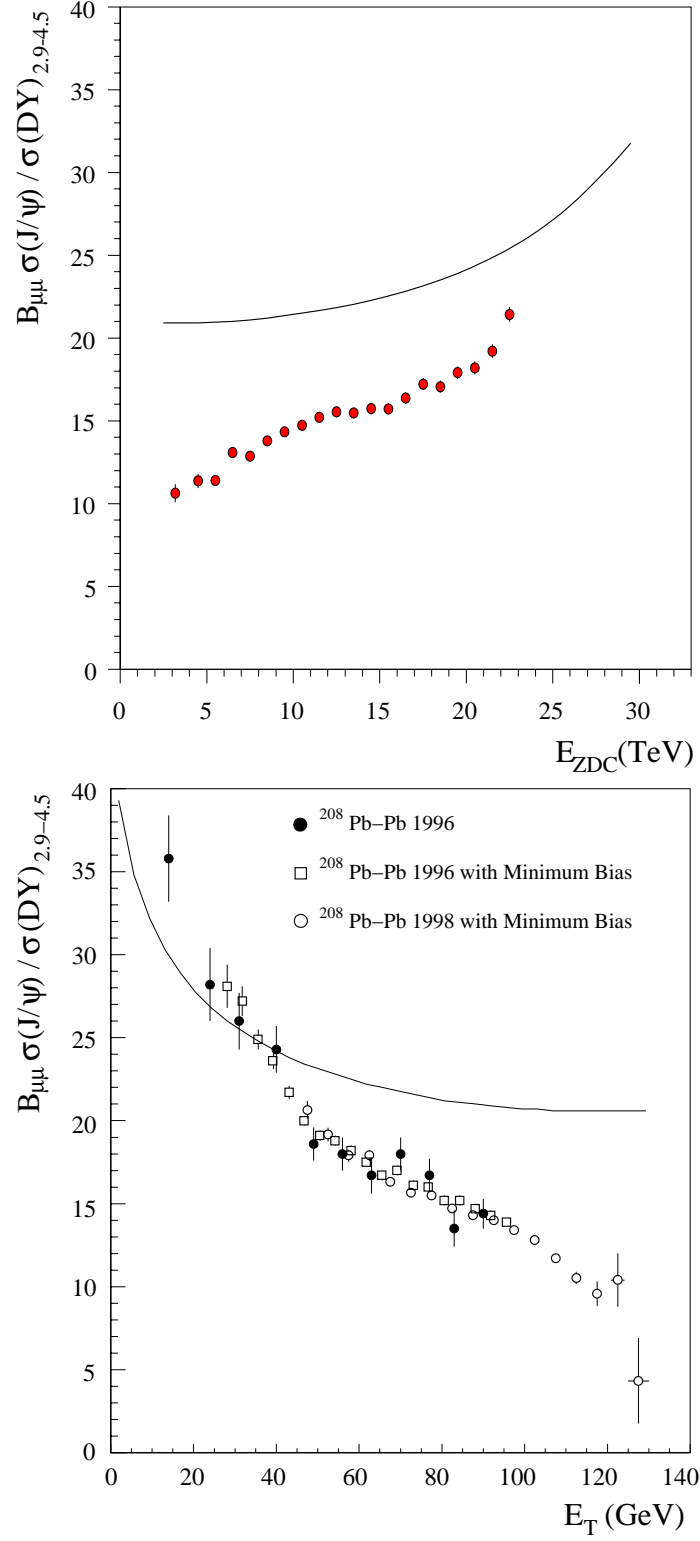


Figure 22: The  $J/\psi$  suppression pattern as a function of the forward (top) and transverse (bottom) energy, in Pb-Pb collisions, as measured by NA50.

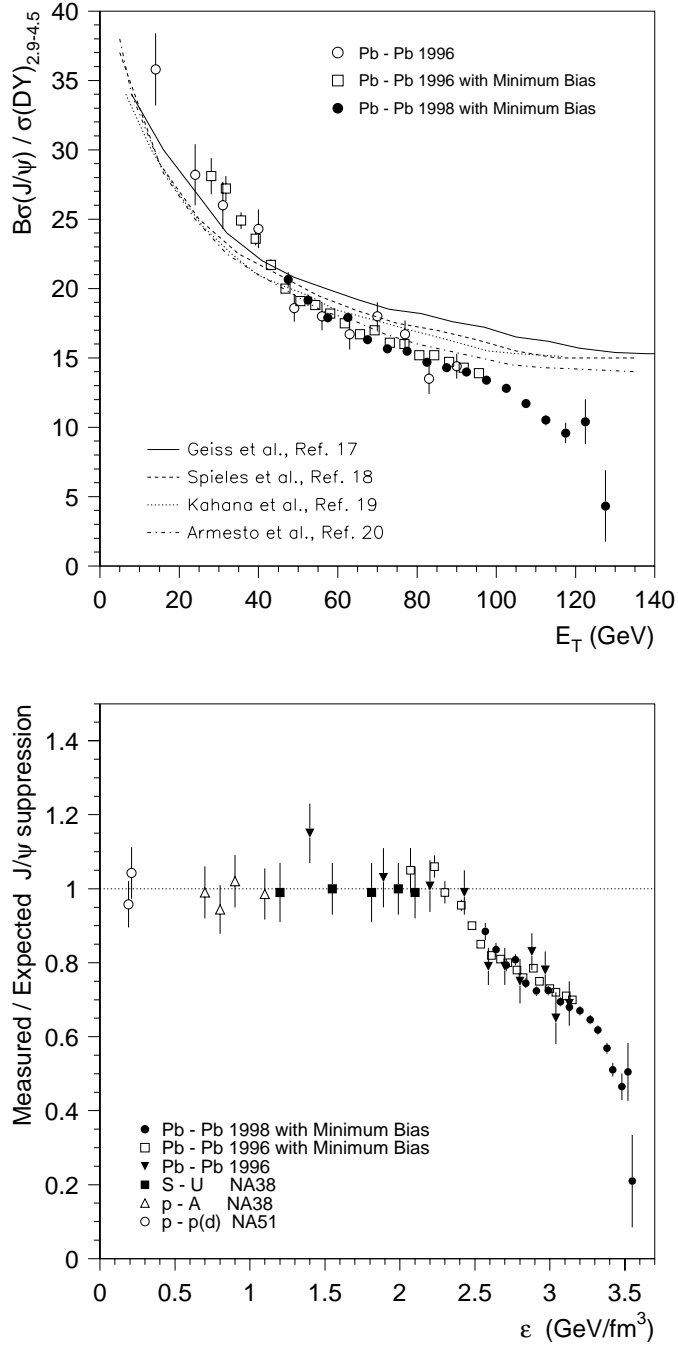


Figure 23: The measured  $J/\psi$  suppression pattern rules out the presently available conventional models (top) and is in qualitative agreement with the two-step pattern expected in the deconfinement picture (bottom).

result from the decay of  $\chi_c$  states). The addition of the pp, p-A and S-U results makes the lower panel of Fig. 23 particularly illustrative of the unconventional nature of the observed  $J/\psi$  suppression pattern.

If we accept that this pattern indicates the production of a state of matter where colour is no longer confined, we must move on to the detailed understanding of how deconfinement sets in, and what physics variable governs the threshold behaviour of the ( $\chi_c$ ) suppression: (local) energy density, density of wounded nucleons, of percolation clusters, of produced gluons, etc. This requires collecting data with a smaller nuclear collision system like In-In. Indeed, it is possible to predict at which impact parameter,  $b$ , of In-In collisions is reached the same threshold in (local) energy density, or any other variable, as reached in Pb-Pb collisions of  $b \approx 8$  fm, where the  $\chi_c$  state starts melting.

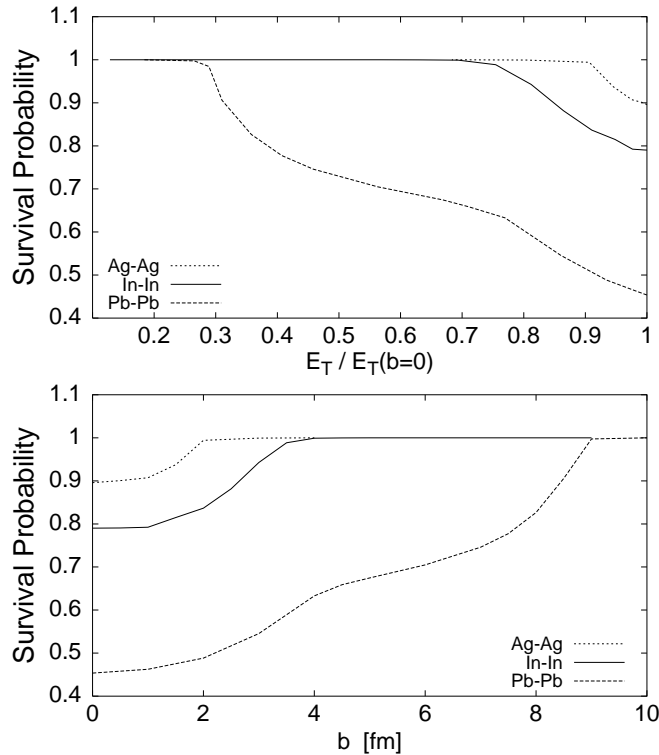


Figure 24: The  $J/\psi$  suppression pattern predicted in a deconfinement model for different collision systems.

According to the deconfinement model used in the calculation [50] shown in Fig. 24, the onset of anomalous  $J/\psi$  suppression should happen at an impact parameter  $b = 2.0\text{--}2.5$  fm, in In-In collisions at 158 A GeV. A verification of such specific predictions would be the final element of proof that the deconfined quark-gluon phase sets in, and would provide fundamental information on the mechanisms behind the observed phenomena. In this context, it is also important to improve our knowledge of the nuclear dependence of  $\chi_c$  production, in p-A collisions, at SPS



energies.

The  $J/\psi$  data do not provide a direct measurement of the critical temperature. Finite temperature lattice QCD tells us that the strongly bound  $J/\psi$   $c\bar{c}$  state should be screened when the medium reaches temperatures 30–40 % higher than  $T_c$ , while the larger and more loosely bound  $\psi'$  state should melt near  $T_c$ . The  $\psi'$  is already significantly suppressed when going from p-U to peripheral S-U collisions but the presently existing results are not clear in what concerns the pattern of the  $\psi'$  suppression. Figure 25 shows the ratio between the  $\psi'$  and Drell-Yan production rates, as a function of  $L$ , the thickness of nuclear matter crossed by the charmonia states. The corresponding  $J/\psi$  (normal nuclear absorption) pattern is also shown, scaled down by the factor 1.64 %. Is the ‘anomalous’  $\psi'$  suppression due to QGP melting or to hadronic absorption? If we see that this suppression happens more or less in an abrupt way, within a single collision system rather than comparing p-U to S-U data, we would know that Debye screening is the mechanism responsible for the  $\psi'$  disappearance and we would have a clear measurement of  $T_c$ . This requires a new measurement, with improved mass resolution to have a cleaner separation between the  $\psi'$  and  $J/\psi$  peaks, and which scans an energy density region including the p-U and the S-U points.

Improved measurements of  $J/\psi$  and  $\psi'$  production, with intermediate mass nuclei, were also included in the wish lists of E. Shuryak and B. Müller, and are an important part of the physics program of the NA60 experiment, which will also measure  $\chi_c$  production in p-A collisions.

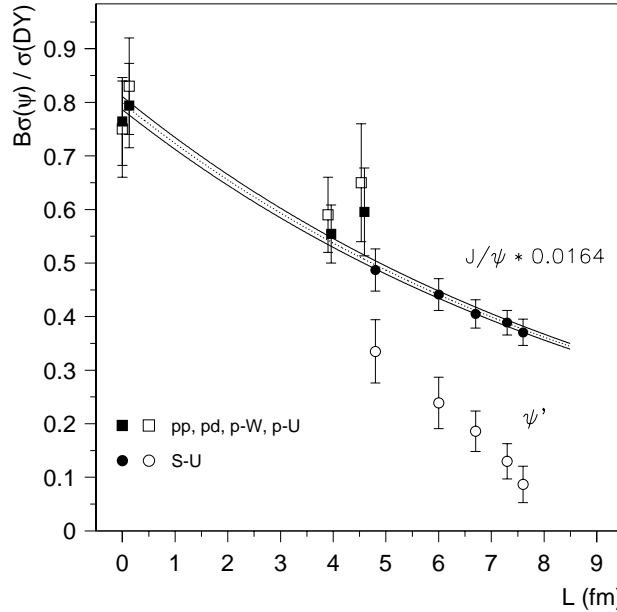


Figure 25: The  $\psi'$  yield is strongly suppressed in S-U collisions. Hadronic absorption or Debye screening?

## 8 Open charm production

Knowing that the bound  $c\bar{c}$  states are suppressed, it is natural to ask what happens to the *unbound* charm. Charm quarks are so heavy that they can only be produced at the earlier stages of the nuclear collision, before the eventual formation of the QGP state. Charm is the heaviest flavour that can be studied in heavy ion collisions at the SPS energies.

The production of charm quarks leads mainly to correlated pairs of  $D$  and  $\bar{D}$  mesons. Only a few percent of the charmed quark pairs end up in the bound charmonia states presently studied by the NA50 experiment, and which exhibit a rather interesting “anomalous” behaviour. What happens to the vast majority of  $c$  quarks? Are they affected by energy loss while crossing the dense (partonic or hadronic) medium? Is charm production enhanced similarly to what has been seen in the strangeness sector?

Finally,  $D$  meson production provides the natural reference with respect to which we should study the observed  $J/\psi$  suppression, since both production mechanisms depend on the same gluon distribution functions. If charm production is enhanced in nuclear collisions, it makes the  $J/\psi$  suppression even more anomalous. A direct observation of  $D$  meson production is clearly the most important new measurement that remains to be done at the SPS, and constitutes a basic reason for the construction and running of NA60.

## 9 Future prospects

The results and open questions presented in the previous sections emphasize the importance of having a new experiment at the SPS, that can significantly improve several existing observations and make a few new measurements, including a measurement of open charm production in heavy ion collisions. A dedicated experiment is needed, that can cope with the very high particle multiplicities reached in the most central nuclear collisions (400 charged particles per unit rapidity at midrapidity) and with the rather small  $D$  production cross section.

The NA50 experiment has been using CERN’s highest intensity heavy ion beam (more than  $10^7$  ions per second) and has a very selective dimuon trigger, quite appropriate to look for rare processes. The recently approved NA60 experiment [51], complements the muon spectrometer and zero degree calorimeter already used in NA50 with two state-of-the-art silicon detectors, placed in the target region: a radiation hard [52] beam tracker, consisting of four silicon microstrip detectors placed on the beam and operated at a temperature of 130 K, and a 10-plane silicon pixel tracking telescope, made with radiation tolerant [53] readout pixel chips, placed in a 2.5 T dipole magnetic field.

The NA60 experiment has been approved to run from 2001 to 2003, using proton, Pb and In beams. The following questions summarize the physics motivation of NA60.

- What is the origin of the dimuon excess seen in the intermediate mass region? Thermal dimuon production?
- Is the open charm yield enhanced in nucleus-nucleus collisions? How does it compare to the suppression pattern of bound charm states?
- What is the variable (local energy density, cluster density, etc.) that rules the onset of charmonia suppression?
- What is the physical origin of the  $\psi'$  suppression? If it is due to Debye screening, what is its melting temperature?
- Which fraction of the  $J/\psi$  yield comes from  $\chi_c$  decays? Does it change from p-Be to p-Pb collisions?
- Are there medium induced modifications in the  $\rho$  meson? Is there a threshold behaviour in the low mass dilepton enhancement? What happens with the  $\omega$  meson?
- Is the observed  $\phi$  enhancement a specific feature of heavy ion collisions? Is the  $\phi$  sensitive to flow?

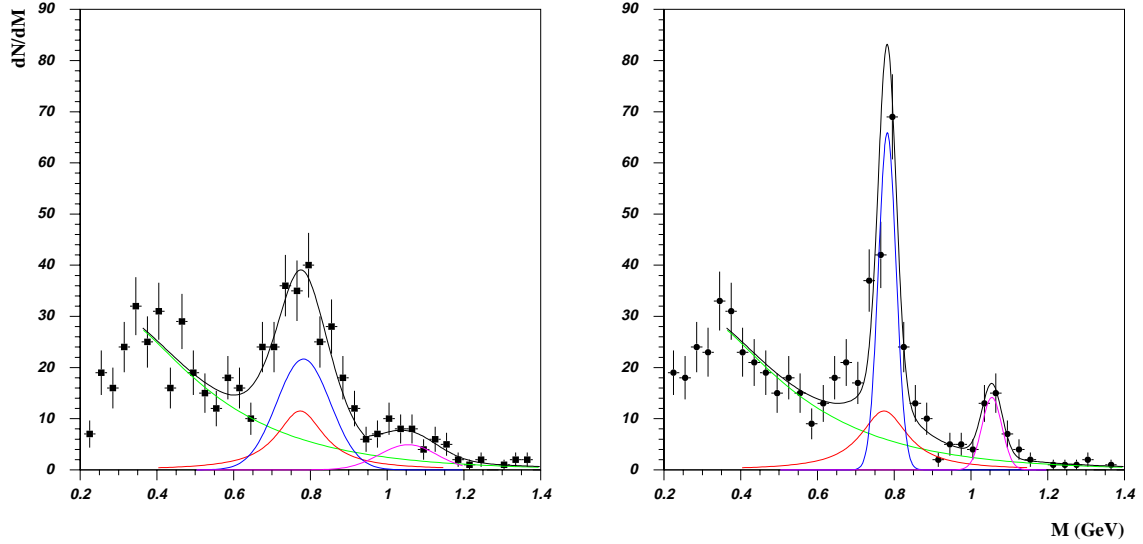


Figure 26: Dimuon mass distributions measured in 1998, in p-Be collisions, before (left) and after (right) using the information of the test pixel telescope. The curves represent the low mass vector meson resonances ( $\rho$ ,  $\omega$  and  $\phi$ ) on the top of a continuum. They are normalized to the same number of events in both figures. The collected statistics (600 events) correspond to a few minutes of NA60 running.

The high granularity tracking telescope, placed in a powerful dipole field, gives access to the muon tracks at the vertex level and vastly improves the mass resolution of the dimuon measurement. This has been demonstrated in a very fast feasibility test done in 1998, using a small telescope (four half-planes) made of the previous generation of readout pixel chips. The results, shown in Fig. 26, confirm that the

mass resolution improves from 70 to 20 MeV at the  $\omega$  mass, as expected from the physics performance simulations illustrated on Fig. 27.

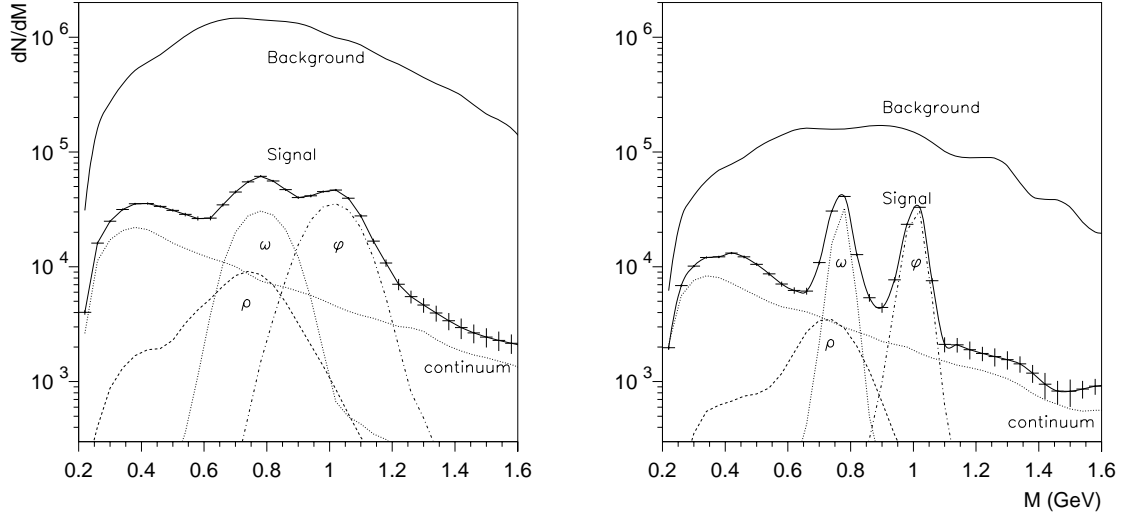


Figure 27: Simulated dimuon mass distribution in Pb-Pb collisions, before (left) and after (right) using the NA60 pixel telescope information. The statistics corresponds to around one week of running.

The NA60 beam tracker gives the transverse coordinates of the interaction point, on the targets, with enough accuracy (around  $20 \mu\text{m}$ ) to measure the impact parameter of the muon tracks, i.e. the minimum distance between the track and the collision vertex, in the transverse plane. Thanks to this information, NA60 will be able to separately study the production of prompt dimuons and the production of muons originating from the decay of charmed mesons, in p-A and heavy ion collisions. The prompt dimuon analysis will use events where both muons come from (very close to) the interaction vertex. The open charm event sample is composed of those events where both muon tracks have a certain minimum offset with respect to the interaction point and a minimal distance between themselves at  $z_{\text{vertex}}$ . Figure 28 shows the simulated mass spectra for both event samples. It should not be difficult to see which of these two event samples is enhanced by a factor of 2 or 3 in nuclear collisions of  $N_{\text{part}} \sim 300$ .

Figure 29 shows the accuracy of the determination of the interaction point, in the transverse plane. Along the beam axis the vertex is found with a precision of  $\sim 100\text{--}150 \mu\text{m}$ . If the incident nucleus makes a peripheral collision and the beam spectators fragment collides further down in the target, the double emission of particles should be distinguishable from what happens in a single (central) collision. This allows the use of a thicker target, with a corresponding gain in total effective luminosity. A high interaction rate is the basis for enough statistics to study the charmonia production yield in many centrality bins, a necessary condition to accurately determine a step-

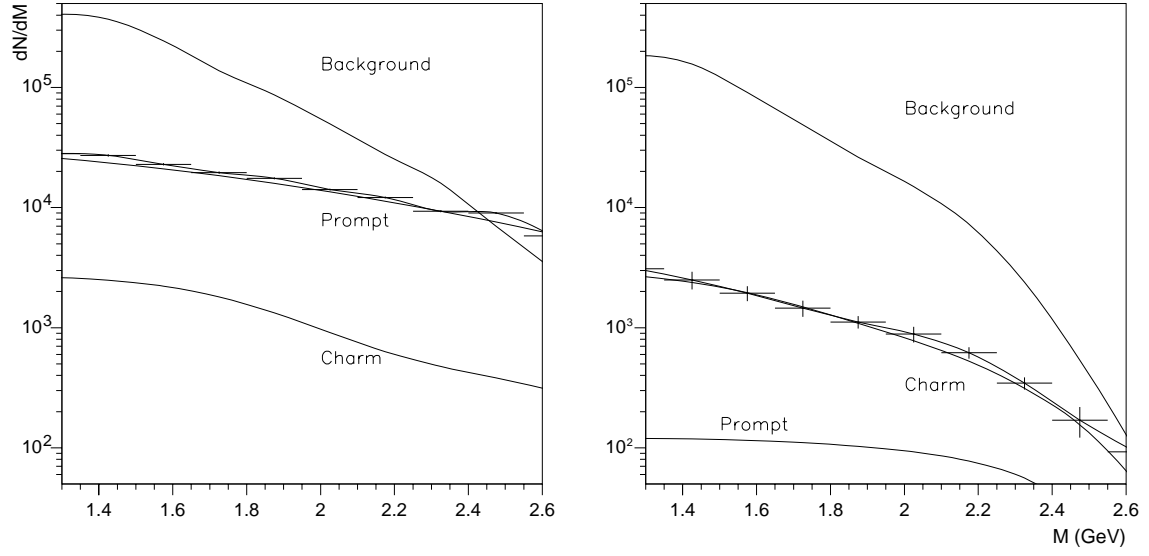


Figure 28: Simulated dimuon mass distributions for the prompt (left) and charm (right) event selections. The background contribution is also shown, including pion/kaon decays and fake matches between the tracks in the muon and in the vertex spectrometers. The error bars in the signal points include the uncertainty from background subtraction.

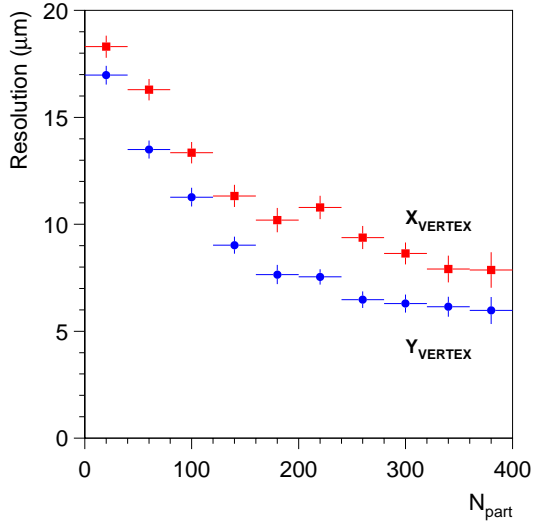


Figure 29: Calculated resolution in the determination of the transverse coordinates of the interaction vertex.

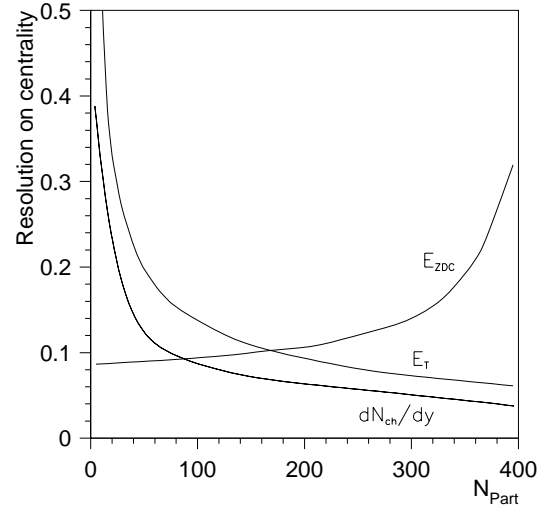


Figure 30: Resolution on the measurement of the centrality of the collisions, using three different estimators.

wise suppression pattern. Besides statistics, it is also important to have a good accuracy in the measurement of the centrality of the collision. Figure 30 shows that a resolution between 5 % and 10 %, depending on the centrality, should be reached in NA60, using the forward energy,  $E_{\text{ZDC}}$ , and the charged particle multiplicity,  $dN_{\text{ch}}/dy$ .

The studies of prompt dimuon and open charm production in p-A collisions are important reference measurements, to understand the results obtained with nuclear collisions. In particular, the ratio between the open charm and the Drell-Yan production cross sections will be determined with high accuracy in several p-A collision systems, revealing if these two hard processes have the same A-dependence or not. Figure 31 illustrates the foreseeable analysis of intermediate mass dimuons production, in p-Be or p-Pb collisions, showing the  $p_T$  distribution of the prompt dimuons and the mass distribution of the open charm events.

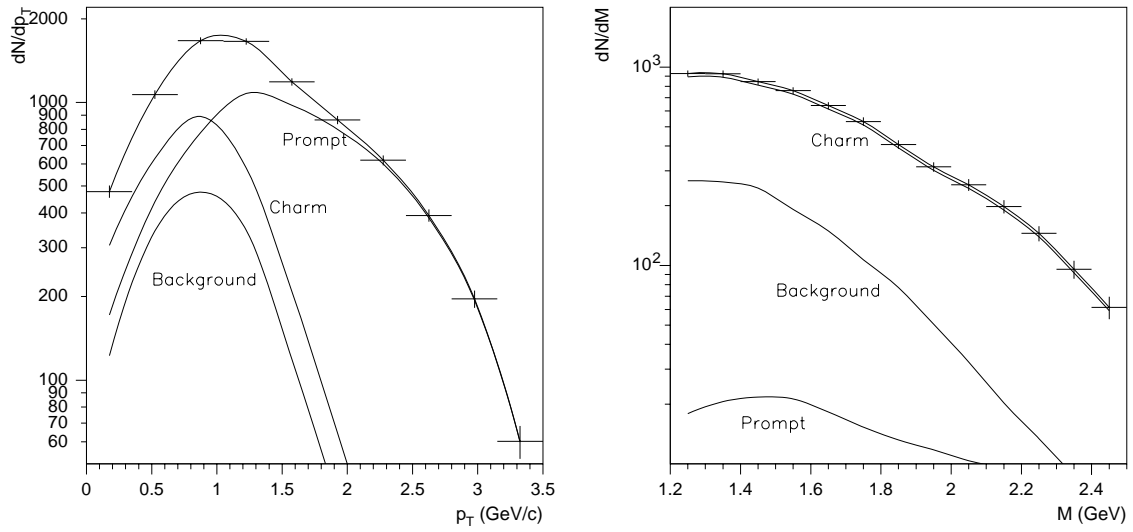


Figure 31: Expected prompt (left) and charm (right) event samples selected in proton induced collisions.

More challenging will be the measurement of the dependence of  $\chi_c$  production on the mass number of the target, in p-A collisions, by seeing how the ratio between  $\chi_c$  and  $J/\psi$  yields changes from p-Be to p-Pb collisions. To minimize the systematical uncertainties due to the beam flux normalization, the measurement will be done using the Be and Pb targets simultaneously in the beam. The  $\chi_c \rightarrow \psi \gamma \rightarrow \psi e^+ e^-$  decays will be used for this study, with the photons converting in a Pb disk placed downstream of the targets, and the electron-positron pairs reconstructed in the silicon pixel telescope.

## 10 Summary and conclusions

Starting from the questions and wishes expressed at the Quark Matter 1999 conference, concerning measurements that should be done at the CERN SPS before closing

this facility, I have briefly mentioned some of the most recent developments and emphasized the issues that have imposed a continuation of the SPS heavy ion physics program.

After 15 years of “learning curve”, we can say that we have been unable to falsify the hypothesis of quark gluon plasma formation at the CERN SPS. In fact, as predicted, strangeness is enhanced, the  $J/\psi$  is suppressed, the dimuon continuum looks as if thermal dileptons are produced, and there are modifications in the low mass dilepton spectra, among other observations. These results provide extremely relevant information about the (predicted) formation of a deconfined state of matter in high energy heavy ion collisions. However, considerable homework remains to be done in view of converting “compelling evidence” into “conclusive evidence” that the quark matter phase has indeed been formed at CERN. This is exactly the reason why the heavy ion community must make a significant effort to further clarify the present results and reach a deeper understanding of the critical behaviour of QCD at SPS energies.

The re-birth of the heavy ion physics program at the CERN SPS, with the extension of NA49 and the approval of the new NA60 experiment, represents an evolution from a broad physics program to a dedicated study of specific signals that already provided very interesting results. The new measurements of NA60 should give a significant contribution to the understanding of the presently existing results, and considerably help in building a convincing logical case that establishes beyond reasonable doubt the formation (or not) of a deconfined state of matter in heavy ion collisions at the SPS.

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